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A filtered no arbitrage model for term structures from noisy data

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Abstract

We consider an affine term structure model of interest rates, where the factors satisfy a linear diffusion equation. We assume that the information available to an agent comes from observing the yields of a finite number of traded bonds and that this information is not sufficient to reconstruct exactly the factors. We derive a method to obtain arbitrage-free prices of illiquid or non traded bonds that are compatible with the available incomplete information. The method is based on an application of the Kalman filter for linear Gaussian systems.

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1. Introduction

We study multifactor affine term structure models of interest rates (see e.g. [6,9]), where the factors $x(t)$ satisfy a linear diffusion equation. The factors may be viewed as representing market fundamentals, but in our context they need not have a

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specific interpretation and may just be viewed as abstract factors. They are considered as latent variables that are not directly observable, but can be estimated (filtered) from observations of traded bond yields.

The purpose is to derive a consistent pricing system to price illiquid and non traded bonds on the basis of the incomplete information available to agents. We assume that this incomplete/partial information, represented by a subfiltration $\hat{\mathcal{F}}_t \subset \mathcal{F}_t$ of the full filtration \mathcal{F}_t , comes from observing the prices $\tilde{p}(t, T_i)$ (or corresponding yields) of a finite number N of traded bonds. The crucial further assumption is that this information is not sufficient to completely reconstruct the factors x_t . More precisely, we assume that each of the N observations comes with additional uncertainty and that the additional uncertainty sources together form a further factor $\xi(t)$ of dimension N . This happens e.g. in the realistic situation when the actually observed term structure does not correspond exactly to a theoretical arbitrage-free factor model. We call the thus resulting term structure model the “perturbed model”. Assuming a situation of this latter type, we derive a method to obtain arbitrage-free prices $\hat{p}(t, T)$ of non traded (illiquid) bonds that are compatible with the available partial information $\hat{\mathcal{F}}_t$ and we call this the projected price system. Specifically, we obtain the formula

$$\hat{p}(t, T) = \frac{E^Q[\tilde{p}(t, T)/\tilde{M}(t)|\hat{\mathcal{F}}_t]}{E^Q[1/\tilde{M}(t)|\hat{\mathcal{F}}_t]}, \quad (1)$$

where $\tilde{p}(t, T)$ are the bond prices in the perturbed model; $\tilde{M}(t)$ is the corresponding money market account and Q a given risk-neutral (martingale) measure. To this effect we derive some intermediate results justifying formula (1).

Thanks to (1), the computation of the projected price system reduces to the computation of the conditional expectations on the right-hand side of (1). It is then shown that these conditional expectations can be computed if one can compute means and covariances of the vector of the original and latent factors $(x(t), \xi(t))$, conditional on $\hat{\mathcal{F}}_t$. This is where stochastic filtering comes in and we show that it reduces to an application of the classical Kalman filter for linear-Gaussian systems. This method extends thus in a nontrivial way a previous related work by two of the authors [13].

Instead of the “economic” definition of the filtered term structure through (1), it is possible to define the filtered forward rates using the filtered factors from the Kalman filter and applying the HJM-no-arbitrage condition. We show that, in the case of linear factor models, the two definitions are equivalent.

Stochastic filtering techniques have recently found various applications in finance, in particular also in the context of the term structure of interest rates as e.g. in [1,2,4,5,10,11,15]. The context of these latter papers is however different from that of the present work.

In the next Section 2 we introduce the basic theoretical arbitrage-free affine term structure model. The perturbed model is then described in Section 3. In Section 4 we show how to derive from the perturbed model the projected pricing system. In Section 5 we then show how the projected price system can actually be computed by

use of Kalman filtering. In Section 6 we show the equivalence of the two alternative definitions of the filtered term structure.

It should be noted that the results of the paper—with the exception of those of Section 5, which are extended to a more general setup in [12]—rely on the Gaussianity assumption and on the linearity of the term structure model.

2. Notation and preliminary results

We consider a class of interest rate models which are the output of a time-varying linear Gaussian system. Given a filtered probability space $(\Omega, \mathcal{F}, \mathcal{F}_t, Q)$, assume that we have an n -dimensional diffusion

$$\begin{aligned} dx(t) &= A(t)x(t)dt + B(t)dw(t), \\ x_0 &= 0, \end{aligned} \quad (2)$$

where $A(t)$ and $B(t)$ are $n \times n$ and $n \times m$ matrices, respectively, which depend only on t , w is an m -dimensional Wiener-process. We will show in the sequel that the assumption $x_0 = 0$ is not restrictive. The matrices A and B are assumed to be locally bounded. We assume moreover that $A(t)$ and $A(s)$ commute, for all $t, s \geq 0$ (it is well known that this is equivalent to assuming that, for each t , it is $A(t) = \phi_0(t)I + \phi_1(t)A + \dots + \phi_{n-1}(t)A^{n-1}$, where A is a constant matrix and the scalar functions $\phi_0, \dots, \phi_{n-1}$ are locally bounded). The forward rates are given by

$$f(t, T) = C(t, T)x(t) + G(t, T), \quad (3)$$

where we assume that the functions $t \mapsto C(t, T)$ and $t \mapsto G(t, T)$ are differentiable.

As usual, $p(t, T) = \exp\{-\int_t^T f(t, s)ds\}$ is the time- t price of the zero-bond maturing at T , $r(t) = f(t, t)$ is the instantaneous short rate, and $M(t) = \exp\{\int_0^t r(s)ds\}$ is the money market account. Let $f^*(0, T)$ denote the observed forward rates at time 0. Setting $C(t) := C(t, t)$ and $G(t) := G(t, t)$, the short rate has the representation

$$\begin{aligned} dx(t) &= A(t)x(t)dt + B(t)dw(t), \\ r(t) &= C(t)x(t) + G(t). \end{aligned}$$

For a generic choice of the functions $C(t, T)$ and $G(t, T)$ one may introduce arbitrage possibilities into the bond market. The next proposition gives conditions on $C(t, T)$ and $G(t, T)$ so that arbitrage possibilities are excluded. As usual for term structure models, we equivalently show that, under those conditions, the measure Q on our probability space is a martingale measure that corresponds to the money market account as numeraire.

Proposition 2.1. *A necessary and sufficient condition for Q to be a risk-neutral probability measure for the term structure model (2), (3) w.r.t. the numeraire M is that the coefficients $C(t, T)$, $G(t, T)$ in (3) satisfy the following:*

$$C(t, T) = C(T)e^{\int_t^T A(s)ds}, \quad (4)$$

where $C(T)$ is a locally bounded function, and

$$G(t, T) = f^*(0, T) + \frac{1}{2} \int_0^t \beta_T(s, T) \, ds, \quad (5)$$

with

$$\beta(t, T) := \left\| \int_t^T C(t, u) B(u) \, du \right\|^2. \quad (6)$$

Proof. Differentiation with respect to t yields

$$\begin{aligned} df(t, T) &= C_t(t, T)x(t) \, dt \\ &\quad + C(t, T)A(t)x(t) \, dt + C(t, T)B(t) \, dw(t) + G_t(t, T) \, dt. \end{aligned} \quad (7)$$

Now, the Heath–Jarrow–Morton drift condition [14] reads

$$\mu(t, T) = C(t, T)B(t) \int_t^T B(t)' C(t, u)' \, du, \quad (8)$$

where $\mu(t, T)$ is the drift and $\sigma(t, T) = C(t, T)B(t)$ is the diffusion coefficient of $f(t, T)$ in (7). Since $x(t)$ does not appear in (8), its coefficients must vanish in (7); thus we obtain

$$C_t(t, T) + C(t, T)A(t) = 0, \quad (9)$$

which has the solution

$$C(t, T) = C(T)e^{\int_t^T A(s) \, ds}.$$

thereby proving (4). The deterministic term must satisfy the equation

$$\begin{aligned} G_t(t, T) &= C(t, T)B(t)B(t)' \int_t^T C'(t, u) \, du \\ &= \frac{1}{2} \frac{\partial}{\partial T} \left\| \int_t^T C(u)e^{\int_t^u A(s) \, ds} B(u) \, du \right\|^2 = \frac{1}{2} \beta_T(t, T), \end{aligned} \quad (10)$$

where we have used (4). As a consequence of (3) we get $G(0, T) = f^*(0, T)$. Thus, (10) and (5) are equivalent.

This proves that conditions (4) and (5) are a consequence of (8); conversely, if (4) and (5) are satisfied, then that part of the drift in (7) that is linear in x vanishes due to (9), and the drift term is given by (10). This proves the equivalence to the HJM drift condition, which is necessary and sufficient for $p(\cdot, T)/M$ to be local (Q, \mathcal{F}) -martingales. Novikov's condition for $p(\cdot, T)/M$ to be a martingale on $[0, T]$ is

$$E \left[\exp \left(\frac{1}{2} \int_0^T \beta(s, T) \, ds \right) \right] < \infty,$$

which is fulfilled since A , B , and $C(\cdot)$ are locally bounded. \square

The moral is that, given the functions f^* , A , B , and $C(\cdot)$, the functions $C(t, T)$ and $G(t, T)$ are completely determined by the no arbitrage assumption.

The quantity $G(t, T)$ can be computed in an almost closed form, as we shall see in Section 5; however, if $A, B, C(\cdot)$ are constant in t and A is invertible, things simplify even further and we have (see [3])

$$G(t, T) = f^*(0, T) + \frac{1}{2} \{ \|CA^{-1}e^{AT}B\|^2 - \|CA^{-1}e^{A(T-t)}B\|^2 \} \\ + CA^{-1} [e^{A(T-t)} - e^{AT}] BB' A'^{-1} C'. \quad (11)$$

We now show that the forward rates $f(t, T)$ are independent of the initial condition x_0 . Suppose that in (2) we have an arbitrary initial condition x_0 independent of w and denote by $f^0(t, T)$ the corresponding term structure; then, denoting by $G^0(t, T)$ the correction term, since we want $f^0(0, T) = f^*(0, T)$ to hold, it must be $G^0(0, T) = -C(0, T)x_0 + f^*(0, T)$, which implies that

$$G^0(t, T) = -C(0, T)x_0 + f^*(0, T) + \frac{1}{2} \int_0^t \beta_T(s, T) ds \quad (12)$$

with $\beta(t, T)$ as in (6). Then we have the following lemma:

Lemma 2.2. *Let the forward rates $f^0(t, T)$ be given by*

$$dx^0(t) = A(t)x^0(t)dt + B(t)dw(t), \\ f^0(t, T) = C(t, T)x^0(t) + G^0(t, T), \quad (13)$$

with initial condition $x^0(0) = x_0$, and $C(t, T)$ as in (4), and let $G^0(t, T)$ be as in (12). Then the term structure $f^0(t, T)$ is independent of x_0 .

Proof. The solution to the first equation in (13) is

$$x^0(t) = e^{\int_0^t A(s) ds} x_0 + \int_0^t e^{\int_s^t A(u) du} B(s) dw(s).$$

In view of (4), $C(0, T) = C(T)e^{\int_0^T A(s) ds}$, which gives

$$f^0(t, T) = C(t, T)x^0(t) - C(0, T)x_0 + f^*(0, T) + \frac{1}{2} \int_0^t \beta_T(s, T) ds \\ = C(T)e^{\int_t^T A(s) ds} \left[\int_0^t e^{\int_s^t A(u) du} B(s) dw(s) + e^{\int_0^t A(s) ds} x_0 \right] \\ - C(T)e^{\int_0^T A(s) ds} x_0 + f^*(0, T) + \frac{1}{2} \int_0^t \beta_T(s, T) ds \\ = C(t, T)x(t) + f^*(0, T) + \frac{1}{2} \int_0^t \beta_T(s, T) ds,$$

where $x(t)$ is the solution to (2) with $x_0 = 0$, as wanted. \square

Note that, since x_0 may now be different from 0, the no arbitrage condition (5) does not hold and a more general expression involving x_0 should be used. However,

as the previous lemma shows, this is not really extending the generality of the results, and so this extension is redundant and has been omitted.

Remark 2.3. If the number N of bonds on the market is greater than the dimension n of the state x , the latter can generally be exactly reconstructed from the knowledge of their yields.

In fact, let $y(t, T) := \int_t^T f(t, s) ds$ denote the time- t yield of the zero-bond maturing at T and assume these yields are observed for the maturities $T_1 < T_2 < \dots < T_n$ with $n \leq N$.

Setting

$$\mathbf{M}(t) = \begin{bmatrix} \int_t^{T_1} C(s) e^{\int_t^s A(u) du} ds \\ \int_t^{T_2} C(s) e^{\int_t^s A(u) du} ds \\ \vdots \\ \int_t^{T_n} C(s) e^{\int_t^s A(u) du} ds \end{bmatrix},$$

we get, from (3) and using (4)

$$\begin{bmatrix} y(t, T_1) \\ y(t, T_2) \\ \vdots \\ y(t, T_n) \end{bmatrix} = \mathbf{M}(t) \begin{bmatrix} x_1(t) \\ x_2(t) \\ \vdots \\ x_n(t) \end{bmatrix} + \begin{bmatrix} \int_t^{T_1} G(t, u) du \\ \int_t^{T_2} G(t, u) du \\ \vdots \\ \int_t^{T_n} G(t, u) du \end{bmatrix}, \quad (14)$$

so that we can obtain x explicitly as soon as \mathbf{M} is invertible. Without further assumptions on A, B, C more precise statements are difficult to make; but in the special case when A, B, C are constant, it can be shown that this situation is generic, i.e., the set of maturities T_1, \dots, T_n , for which \mathbf{M} is rank deficient, is a set contained in an algebraic surface in \mathbb{R}^n (see [3]).

3. The perturbed model

Suppose now that we are in a situation where the state cannot be observed directly. This happens e.g. in the realistic situation when a low-dimensional, parsimonious factor model can describe certain long-term, time-series features of the term structure well, but fails to achieve sufficient accuracy in fitting all the current prices. In this context see e.g. [7,8] in a similar setup. Assume then that the maturities of the actually traded and thus also observed bonds are T_1, \dots, T_N for some integer N and consider the following perturbed version of (3), namely

$$dx(t) = A(t)x(t)dt + B(t)dw(t) \quad (15)$$

$$d\tilde{\xi}(t) = A_{\tilde{\xi}}(t)\tilde{\xi}(t)dt + B_{\tilde{\xi}}(t)dv(t), \quad (16)$$

$$\tilde{f}(t, T) = C(t, T)x(t) + C_{\tilde{\xi}}(t, T)\tilde{\xi}(t) + \tilde{G}(t, T), \quad (t \leq T), \quad (17)$$

where v is an N -dimensional Wiener process, independent of w and $x(0) = 0$, $\tilde{\xi}(0) = 0$. The function $C_{\tilde{\xi}}(s, T)$ is, for fixed T , an N -dimensional row vector of functions that are locally bounded. The function $t \mapsto \tilde{G}(t, T)$ is assumed to be differentiable.

Let then

$$\tilde{p}(t, T) := \exp \left[- \int_t^T \tilde{f}(t, u) du \right], \quad t \leq T \quad (18)$$

and consider as numeraire

$$\tilde{M}(t) := \exp \left[\int_0^t \tilde{r}(s) ds \right], \quad \text{with } \tilde{r}(t) = \tilde{f}(t, t). \quad (19)$$

Eq. (17) together with the dynamics of the extended state

$$\tilde{x}(t) := \begin{bmatrix} x(t) \\ \tilde{\xi}(t) \end{bmatrix} \quad (20)$$

can be written in the same form as the unperturbed system (2)–(3):

$$d\tilde{x}(t) = \tilde{A}(t)\tilde{x}(t)dt + \tilde{B}(t)d\tilde{w}(t), \quad (21)$$

$$\tilde{f}(t, T) = \tilde{C}(t, T)\tilde{x}(t) + \tilde{G}(t, T), \quad (22)$$

with

$$\begin{aligned} \tilde{A}(t) &:= \begin{bmatrix} A(t) & 0 \\ 0 & A_{\tilde{\xi}}(t) \end{bmatrix}, \quad \tilde{B}(t) := \begin{bmatrix} B(t) & 0 \\ 0 & B_{\tilde{\xi}}(t) \end{bmatrix}, \\ \tilde{C}(t, T) &:= [C(t, T), C_{\tilde{\xi}}(t, T)], \quad \tilde{w}(t) := \begin{bmatrix} w(t) \\ v(t) \end{bmatrix}. \end{aligned} \quad (23)$$

Applying Proposition (2.1) to the new system (21)–(22) leads to

Proposition 3.1. *A necessary and sufficient condition for Q to be a risk-neutral probability measure for the term structure $(\tilde{p}(t, T))_{0 \leq t \leq T < \infty}$ with respect to the numeraire \tilde{M}_t is that $\tilde{C}(t, T)$ and $\tilde{G}(t, T)$ in (22) satisfy the following two conditions corresponding to (4) and (5)*

$$\tilde{C}(t, T) = \tilde{C}(T)e^{\int_t^T \tilde{A}(s) ds}, \quad (24)$$

where $\tilde{C}(T)$ is a locally bounded function, and

$$\tilde{G}(t, T) = \tilde{f}^*(0, T) + \frac{1}{2} \int_0^t \tilde{\beta}_T(s, T) ds, \quad (25)$$

where

$$\tilde{\beta}(t, T) := \left\| \int_t^T \tilde{C}(t, u) \tilde{B}(u) du \right\|^2 = \beta(t, T) + \left\| \int_t^T C_{\xi}(t, u) B_{\xi}(u) du \right\|^2. \quad (26)$$

Remark 3.2. In contrast to Remark 2.3 notice now that in our perturbed term structure model, reformulated as (21) and (22), we shall never have enough bonds to reconstruct the (augmented) state \tilde{x} exactly. In fact, the dimension of \tilde{x} is the sum of the dimension n of x and the number N of observations; we have thus N observations to determine an $(n + N)$ -dimensional state. Otherwise said, it is impossible to derive a left invertible matrix \mathbf{M} as in (14).

Remark 3.3. Notice that (15) and (24) yield

$$C_{\xi}(t, T) \xi(t) = C_{\xi}(T) \int_0^T e^{\int_s^T A_{\xi}(\tau) d\tau} B_{\xi}(s) dv(s).$$

Taking $A_{\xi} = 0$, $B_{\xi} = I$ and $C_{\xi}^i(T) := \chi_{(T_{i-1}, T_i]}$, we get the special case discussed in [13].

In what follows we shall therefore suppose that we are in a situation where the state cannot be observed directly and that our (partial) information corresponds to a subfiltration $\hat{\mathcal{F}}_t \subset \mathcal{F}_t$. Typically, and this will be the setting in Section 5 below, $\hat{\mathcal{F}}$ results from the observations of the traded bond prices (or their yields), but for the time being, in particular for the next Section 4, we shall consider a generic subfiltration $\hat{\mathcal{F}}_t \subset \mathcal{F}$ containing the σ -algebra generated by the set of prices $(\tilde{p}(t, T_i))_{i=1, \dots, N}$. Notice that, if $t > T_i$, the filtration $\hat{\mathcal{F}}_t$ measures the entire process $\{\tilde{p}(s, T_i)\}_{0 \leq s \leq T_i}$.

4. The projected price system

In a previous paper [13] two of the authors have studied the problem of constructing a consistent price system under partial information in a similar setting. It relies, however, on the assumption that the perturbed money market account \tilde{M}_t is observed ($\hat{\mathcal{F}}$ -adapted) and liquidly traded, which may be unrealistic.

In the following we present a way of defining an arbitrage-free term structure that is $\hat{\mathcal{F}}$ -adapted, in the case when the money market account \tilde{M} , or another bond price which we would like to use as numeraire, is not observed. Our result can be extended to general arbitrage free markets (see [13]). Here we derive the relevant results in the specific context of the bond market.

Definition 4.1. For a numeraire N with martingale measure Q on a filtration \mathcal{F} , the price system defined by the triple (Q, N, \mathcal{F}) for the \mathcal{F}_t measurable claim X is

$$\Pi_{t,T}(X; Q, N, \mathcal{F}) := N(t) E^Q[X/N(T) | \mathcal{F}_t].$$

In particular, for the observed bond prices one then has

$$\tilde{p}(t, T) = N(t)E^Q[1/N(T) | \mathcal{F}_t]. \quad (27)$$

It is well known that, for bond markets, possible alternatives to the money market account as numeraire are the traded and observed (normalized) zero-bonds $\tilde{M}^i(t) := \tilde{p}(t, T_i)/\tilde{p}(0, T_i)$. For our purposes it is most convenient to choose the bond with the largest maturity T_N . Denoting by Q^N the corresponding martingale measure, we then have

$$\tilde{p}(t, T) = \tilde{p}(t, T_N)E^{Q^N}\left\{\frac{1}{\tilde{p}(T, T_N)}\middle|\mathcal{F}_t\right\} \quad \text{for } t \leq T \leq T_N. \quad (28)$$

If now the actual set of information up to time t is $\hat{\mathcal{F}}_t$, it is natural to consider the projected bond price system according to the following

Definition 4.2 (*the projected price system*). This system will be denoted by $\hat{p}(t, T)$ and is given by

$$\hat{p}(t, T) = \tilde{p}(t, T_N)E^{Q^N}\left\{\frac{1}{\tilde{p}(T, T_N)}\middle|\hat{\mathcal{F}}_t\right\} \quad \text{for } t \leq T \leq T_N. \quad (29)$$

Notice that, since $\tilde{p} \in \hat{\mathcal{F}}$, the projected prices $\hat{p}(t, T)$ are $\hat{\mathcal{F}}$ -adapted processes and, furthermore, $\hat{p}(t, T)/\tilde{p}(t, T_N)$ is a $(Q^N, \hat{\mathcal{F}})$ -martingale $\forall T \leq T_N$, which implies that the system of projected bond prices is arbitrage-free. Notice also that, given (28), formula (29) can also be written as

$$\hat{p}(t, T) = \tilde{p}(t, T_N)E^{Q^N}\left\{\frac{\tilde{p}(t, T)}{\tilde{p}(t, T_N)}\middle|\hat{\mathcal{F}}_t\right\},$$

which in turn simplifies to

$$\hat{p}(t, T) = E^{Q^N}\{\tilde{p}(t, T) | \hat{\mathcal{F}}_t\}. \quad (30)$$

It is immediately seen that the expressions on the right in (29), (30) would lead to the same value if, instead of the bond with maturity T_N , we would have chosen a bond with any of the other maturities $T_i, i = 1, \dots, N$ thereby taking expectation with respect to the corresponding martingale measure Q^i .

What is not very satisfactory in (29) (equivalently (30)) is the restriction $T \leq T_N$. Furthermore, as mentioned above, one would also like to obtain equivalent representations of the same arbitrage-free projected price system $\hat{p}(t, T)$ for the case when the numeraire is not observed. This latter objective and the extension of the definition of \hat{p} also beyond T_N is achieved in the following proposition and its corollary (see also the concluding remark 4.5).

Proposition 4.3. *Let $N(t)$ be a numeraire with corresponding martingale measure Q on \mathcal{F} such that $N(t) \notin \hat{\mathcal{F}}_t$. Then, letting*

$$\hat{N}(t) := 1/E^Q\{1/N(t) | \hat{\mathcal{F}}_t\}, \quad (31)$$

one has

$$\hat{p}(t, T) = \hat{N}(t) E^Q \left\{ \frac{1}{\hat{N}(T)} \middle| \hat{\mathcal{F}}_t \right\}, \quad (32)$$

i.e., the triple $(\hat{N}, Q, \hat{\mathcal{F}})$ is yet another way to represent the same projected price system $\hat{p}(t, T)$.

Proof. The Radon–Nikodym derivative $L^N = dQ^N/dQ$ is given by

$$L^N(t) = \frac{\tilde{M}^N(t)}{N(t)} = \frac{\tilde{p}(t, T_N)}{\tilde{p}(0, T_N)N(t)} \quad \text{on } \mathcal{F}_t. \quad (33)$$

Using the abstract Bayes formula on (29), we get

$$\begin{aligned} \hat{p}(t, T) &= \tilde{p}(t, T_N) \frac{E^Q [L^N(T)/\tilde{p}(T, T_N) | \hat{\mathcal{F}}_t]}{E^Q [L^N(t) | \hat{\mathcal{F}}_t]} \\ &= \tilde{p}(t, T_N) \frac{E^Q \left[\frac{1}{\tilde{p}(0, T_N)N(T)} \middle| \hat{\mathcal{F}}_t \right]}{E^Q \left[\frac{\tilde{p}(t, T_N)}{\tilde{p}(0, T_N)N(t)} \middle| \hat{\mathcal{F}}_t \right]} \\ &= \tilde{p}(t, T_N) \frac{E^Q [1/N(T) | \hat{\mathcal{F}}_t]}{E^Q \left[\frac{\tilde{p}(t, T_N)}{N(t)} \middle| \hat{\mathcal{F}}_t \right]}. \end{aligned} \quad (34)$$

Using the fact that $\tilde{p}(t, T_N)$ is $\hat{\mathcal{F}}_t$ -measurable, this reduces to

$$\hat{p}(t, T) = \frac{E^Q \left[\frac{1}{N(T)} \middle| \hat{\mathcal{F}}_t \right]}{E^Q \left[\frac{1}{N(t)} \middle| \hat{\mathcal{F}}_t \right]}, \quad (35)$$

i.e., by the definition of $\hat{N}(t)$ to

$$\hat{p}(t, T) = \hat{N}(t) E^Q \left\{ \frac{1}{\hat{N}(T)} \middle| \hat{\mathcal{F}}_t \right\}. \quad \square$$

In particular, if the unobserved numeraire is the money market account \tilde{M} with corresponding martingale measure Q then, since $E^Q [1/\tilde{M}(T) | \mathcal{F}_t] = \tilde{p}(t, T)/\tilde{M}(t)$, from Eq. (35) in the above proof we obtain the following corollary.

Corollary 4.4. *The system of bond prices \hat{p} , defined in (29) for $T \leq T_N$, admits the representation (for the second equality see, by analogy, (29) and the formula before (30))*

$$\hat{p}(t, T) = \frac{E^Q \left\{ \frac{1}{\tilde{M}(T)} \middle| \hat{\mathcal{F}}_t \right\}}{E^Q \left\{ \frac{1}{\tilde{M}(t)} \middle| \hat{\mathcal{F}}_t \right\}} = \frac{E^Q \left\{ \frac{\tilde{p}(t, T)}{\tilde{M}(t)} \middle| \hat{\mathcal{F}}_t \right\}}{E^Q \left\{ \frac{1}{\tilde{M}(t)} \middle| \hat{\mathcal{F}}_t \right\}} \quad (36)$$

and this justifies (36) as definition for the projected zero-bond prices also for $0 \leq t \leq T < \infty$ (provided that $f^*(0, T)$ is available for those values of T).

Furthermore, if the money market account \tilde{M} is observable, formula (36) reduces to

$$\hat{p}(t, T) = E^Q[\tilde{p}(t, T) | \hat{\mathcal{F}}_t],$$

thereby recovering the special case of [13].

Remark 4.5. The above results can easily be adapted to the case when the unobserved numeraire is a bond that is not traded or only thinly traded and for which the price is thus not observed. They can also be generalized to the case when, instead of pricing bonds, one wants to price a general claim X that is $\hat{\mathcal{F}}_T$ —adapted (in this context see also [12]).

5. Computation of the projected prices by Kalman filtering

The purpose of this section is to show that the projected price system \hat{p} of the previous Section 4 (see (36)) can actually be computed, for $t < T_N$, by the use of Kalman filtering, if the subfiltration $\hat{\mathcal{F}}_t$ is generated by the N prices $(\tilde{p}(t, T_i))_{i=1, \dots, N}$, or equivalently, the cumulative yields $(\tilde{y}(t, T_i))_{i=1, \dots, N}$ defined by

$$\tilde{y}(t, T) := -\log(\tilde{p}(t, T)) = \int_t^T \tilde{f}(t, s) ds. \quad (37)$$

Notice that for $t > T_N$ the filtration $\hat{\mathcal{F}}_t$ is not increasing and so there is nothing else to be filtered.

Lemma 5.1. Let $\hat{\mathcal{F}}$ be the filtration that is generated by the N yields $(\tilde{y}(t, T_i))_{i=1, \dots, N}$. Then we have

$$\frac{E^Q[\tilde{p}(t, T) / \tilde{M}(t) | \hat{\mathcal{F}}_t]}{E^Q[1 / \tilde{M}(t) | \hat{\mathcal{F}}_t]} = \exp\left\{-\hat{y}(t, T) + \frac{1}{2}\Gamma_1(t, T) + \Gamma_2(t, T)\right\}, \quad (38)$$

with

$$\hat{y}(t, T) := E^Q[\tilde{y}(t, T) | \hat{\mathcal{F}}_t], \quad (39)$$

$$\Gamma_1(t, T) := \text{var}^Q[\tilde{y}(t, T) | \hat{\mathcal{F}}_t], \text{ and} \quad (40)$$

$$\Gamma_2(t, T) := \text{cov}^Q\left[\tilde{y}(t, T), \int_0^t \tilde{f}(s, s) ds \middle| \hat{\mathcal{F}}_t\right]. \quad (41)$$

$\Gamma_1(t, T)$ and $\Gamma_2(t, T)$ are constant as a function of ω , i.e., they are deterministic.

Proof. From the moment generating function of the normal distribution, we have

$$E[e^Y | \mathcal{F}] = e^{E[Y | \mathcal{F}] + \frac{1}{2}\text{var}[Y | \mathcal{F}]}, \quad (42)$$

whenever the conditional distribution of some random variable Y under some σ -algebra \mathcal{F} is Gaussian. (The second term in the exponent is the variance of the conditional distribution of Y given \mathcal{F} , $\text{var}[Y|\mathcal{F}] = E[(Y - E[Y|\mathcal{F}])^2|\mathcal{F}]$.)

Thus, in view of (42), we can write

$$\begin{aligned} \frac{E^Q[\tilde{p}(t, T)/\tilde{M}(t)|\hat{\mathcal{F}}_t]}{E^Q[1/\tilde{M}(t)|\hat{\mathcal{F}}_t]} &= \frac{E^Q[\exp\{-\tilde{y}(t, T) - \int_0^t \tilde{f}(s, s) ds\}|\hat{\mathcal{F}}_t]}{E^Q[\exp\{-\int_0^t \tilde{f}(s, s) ds\}|\hat{\mathcal{F}}_t]} \\ &= \frac{\exp\left\{E^Q[-\tilde{y}(t, T) - \int_0^t \tilde{f}(s, s) ds|\hat{\mathcal{F}}_t] + \frac{1}{2}\Sigma_1\right\}}{\exp\left\{E^Q[-\int_0^t \tilde{f}(s, s) ds|\hat{\mathcal{F}}_t] + \frac{1}{2}\Sigma_2\right\}}, \end{aligned} \quad (43)$$

where

$$\begin{aligned} \Sigma_1 &= \text{var}^Q\left[-\tilde{y}(t, T) - \int_0^t \tilde{f}(s, s) ds \middle| \hat{\mathcal{F}}_t\right] \\ &= \text{var}^Q[\tilde{y}(t, T)|\hat{\mathcal{F}}_t] + \text{var}^Q\left[\int_0^t \tilde{f}(s, s) ds \middle| \hat{\mathcal{F}}_t\right] \\ &\quad + 2\text{cov}^Q\left[\tilde{y}(t, T), \int_0^t \tilde{f}(s, s) ds \middle| \hat{\mathcal{F}}_t\right] \end{aligned} \quad (44)$$

and

$$\Sigma_2 = \text{var}^Q\left[\int_0^t \tilde{f}(s, s) ds \middle| \hat{\mathcal{F}}_t\right]. \quad (45)$$

Putting (44) and (45) into (43) and cancelling terms, gives (38).

Given random variables X , Y , Z that are joint normally distributed, X and $(Y - E[Y|X])(Z - E[Z|X])$ are independent, since X and $Y - E[Y|X]$ as well as X and $Z - E[Z|X]$ are uncorrelated. Thus, the conditional covariance

$$\text{cov}[Y, Z|X] = E[(Y - E[Y|X])(Z - E[Z|X])|X],$$

is actually the constant

$$E[(Y - E[Y|X])(Z - E[Z|X])].$$

This applies to Γ_1 and Γ_2 since all forward rates $\tilde{f}(t, T)$ and yields $\tilde{y}(t, T)$ are joint normally distributed. \square

As a consequence of the lemma we see that our goal is achieved if we are able to compute explicitly the conditional means and variances in (39)–(41).

The conditional mean (39) in the exponent (38) can be computed by means of a Kalman filter and this is what we are going to derive now. In order to make the

partially observed system more compact, define

$$\tilde{z}(t) := \begin{bmatrix} \tilde{y}(t, T_1) - \int_t^{T_1} \tilde{G}(t, u) du \\ \tilde{y}(t, T_2) - \int_t^{T_2} \tilde{G}(t, u) du \\ \vdots \\ \tilde{y}(t, T_N) - \int_t^{T_N} \tilde{G}(t, u) du \end{bmatrix}, \quad \text{for } t \leq T_1 \quad (46)$$

and, since in the interval $T_{i-1} < t \leq T_i$ the bonds up to T_{i-1} have expired, we set

$$\tilde{z}(t) := \begin{bmatrix} \tilde{y}(t, T_i) - \int_t^{T_i} \tilde{G}(t, u) du \\ \tilde{y}(t, T_{i+1}) - \int_t^{T_{i+1}} \tilde{G}(t, u) du \\ \vdots \\ \tilde{y}(t, T_N) - \int_t^{T_N} \tilde{G}(t, u) du \end{bmatrix}, \quad \begin{array}{l} \text{for } T_{i-1} < t \leq T_i \\ \text{and } i = 2, \dots, N. \end{array} \quad (47)$$

Taking into account (22), (24), (37), and putting $\tilde{C}(t) := \tilde{C}(t, t)$, $\tilde{G}(t) := \tilde{G}(t, t)$, we obtain the yield dynamics

$$\begin{aligned} d\tilde{y}(t, T) &= -\tilde{f}(t, t) dt + \int_t^T d\tilde{f}(t, s) ds \\ &= -\tilde{C}(t)\tilde{x}(t) dt - \tilde{G}(t) dt \\ &\quad + \left(\int_t^T \tilde{C}(t, u) du \tilde{B}(t) \right) d\tilde{w}(t) + \left(\int_t^T \tilde{G}(t, u) du \right) dt, \end{aligned} \quad (48)$$

giving

$$d\tilde{z}(t) = - \begin{bmatrix} \tilde{C}(t) \\ \tilde{C}(t) \\ \vdots \\ \tilde{C}(t) \end{bmatrix} \tilde{x}(t) dt + \begin{bmatrix} \int_t^{T_i} \tilde{C}(t, u) du \tilde{B}(t) \\ \int_t^{T_{i+1}} \tilde{C}(t, u) du \tilde{B}(t) \\ \vdots \\ \int_t^{T_N} \tilde{C}(t, u) du \tilde{B}(t) \end{bmatrix} d\tilde{w}(t), \quad \begin{array}{l} \text{for } T_{i-1} \leq t \leq T_i \\ \text{and } i = 1, \dots, N. \end{array} \quad (49)$$

The partially observed system can now be written as

$$\begin{aligned} d\tilde{x}(t) &= \tilde{A}(t)\tilde{x}(t) dt + \tilde{B}(t) d\tilde{w}(t), \\ d\tilde{z}(t) &= C_e(t)\tilde{x}(t) dt + V(t) d\tilde{w}(t), \end{aligned} \quad (50)$$

with $C_e(t)$ and $V(t)$ being the terms in brackets in the Eq. (49). System (50) is a classical linear-Gaussian system, to which one can apply the Kalman filter, where $\tilde{x}(t)$ is the unobservable component and $\tilde{z}(t)$ is the observable one. Clearly,

$$\hat{\mathcal{F}}_t = \sigma\{\tilde{z}(s), s \leq t\} \quad (51)$$

and the following proposition follows from standard Kalman filtering theory (see e.g. [16, Theorem 10.3, p. 396]).

Proposition 5.2. *Let the system $(\tilde{x}(t), \tilde{z}(t))$ satisfy (50) and $\hat{\mathcal{F}}_t$ be given by (51). Then the conditional distribution of $\tilde{x}(t)$, given $\hat{\mathcal{F}}_t$, is Gaussian with mean*

$$\hat{x}(t) := E^Q[\tilde{x}(t)|\hat{\mathcal{F}}_t] \quad (52)$$

and covariance matrix

$$\bar{P}(t) := \text{var}^Q[\tilde{x}(t)|\hat{\mathcal{F}}_t], \quad (53)$$

which is deterministic

$$= E^Q[(\tilde{x}(t) - \hat{x}(t))(\tilde{x}(t) - \hat{x}(t))']. \quad (54)$$

Assuming that the matrix

$$D(t) := [V(t)V(t)']^{1/2} \quad (55)$$

is invertible, the conditional mean has the dynamics

$$d\hat{x}(t) = \tilde{A}(t)\hat{x}(t)dt + \hat{B}(t)d\hat{w}(t), \quad (56)$$

with $\hat{x}_0 = 0$,

$$\hat{B}(t) = (\tilde{B}(t)V(t)' + \bar{P}(t)C_e(t)')[D(t)]^{-1} \quad (57)$$

and $\hat{w}(t)$ is the innovations process

$$d\hat{w}(t) = D(t)^{-1}[d\tilde{z}(t) - C_e(t)\hat{x}(t)dt]. \quad (58)$$

Furthermore, $\bar{P}(t)$ is the solution of the Riccati equation

$$\frac{d\bar{P}}{dt} = \tilde{A}\bar{P} + \bar{P}\tilde{A}' - [\tilde{B}V' + \bar{P}C_e'](DD')^{-1}[\tilde{B}V' + \bar{P}C_e]' + \tilde{B}\tilde{B}', \quad (59)$$

with initial condition $\bar{P}(0) = 0$.

It should be noted that, for $t = T_i$, the i th bond expires, and thus the i th component of the \tilde{z} process is dropped. This means, in practice, that we have a sequence of Kalman filters for $t < T_N$, with a decreasing number of observations. For $t > T_N$ there are no observations and thus the innovations process is 0; in other words, the filtered dynamics has no input and evolves freely. This implies that, at each T_i , we re-initialize our filter to get a lower dimensional innovation process, but starting from the mean $\hat{x}(T_i)$ and variance $\mathbf{P}(T_i)$ obtained by the previous filter. It does therefore make sense to consider $\hat{x}(t)$ as a unique process with variance $\bar{P}(t)$.

We have used the symbol D' although D is symmetric, to follow the standard notation for the Kalman filter. It should be noted that the term appearing on the right-hand side of (59) for $t = 0$, $\bar{P}(0) = 0$ is

$$\tilde{B}(I - V'(VV')^{-1}V)\tilde{B}'. \quad (60)$$

Now, $V'(VV')^{-1}V$ is the projector on the column-space (image) of $V'(t)$ in \mathbb{R}^{m+N} . Since, for $t < T_1$, $V(t)$ has dimensions $N \times (m + N)$, it cannot have full rank; on the other hand we can assume, without loss of generality, that \tilde{B} has full column rank for

$t < T_1$. Consequently, (60) cannot be zero, and thus the solution to (59) does not vanish identically.

Proposition 5.2 yields the means to compute the conditional mean $\hat{y}(t, T)$ as

$$\hat{y}(t, T) = E^Q[\tilde{y}(t, T) | \hat{\mathcal{F}}_t] = \int_t^T \tilde{C}(t, u) du \hat{x}(t) + \int_t^T \tilde{G}(t, u) du. \quad (61)$$

The conditional variance of $\tilde{y}(t, T)$ can be computed similarly:

Lemma 5.3. Suppose $\tilde{f}(t, T)$ has dynamics as in (22) and $\hat{\mathcal{F}}_t$ is as in (51) and let \bar{P} be the solution to (59). Then the functions Γ_1 and Γ_2 in (38) are given by

$$\Gamma_1(t, T) = \left\{ \left[\int_t^T \tilde{C}(t, u) du \right] \bar{P}(t) \left[\int_t^T \tilde{C}'(t, u) du \right] \right\}$$

and

$$\Gamma_2(t, T) = \left\{ \int_0^t \tilde{C}(u, u) \bar{P}(u) e^{\int_u^t A'(\tau) d\tau} du \right\} \int_t^T \tilde{C}'(t, u) du.$$

Proof.

$$\begin{aligned} \Gamma_1(t, T) &= \text{var}^Q[\tilde{y}(t, T) | \hat{\mathcal{F}}_t] = E^Q[(\tilde{y}(t, T) - \hat{y}(t, T))^2] \\ &= E^Q \left[\left(\int_t^T \tilde{C}(t, u) du (\tilde{x}(t) - \hat{x}(t)) \right)^2 \right] \\ &= E^Q \left[\int_t^T \tilde{C}(t, u) du (\tilde{x}(t) - \hat{x}(t)) (\tilde{x}(t)' - \hat{x}(t)') \int_t^T \tilde{C}'(t, u) du \right] \\ &= \left\{ \int_t^T \tilde{C}(t, u) du \right\} \bar{P}(t) \left\{ \int_t^T \tilde{C}'(t, u) du \right\}. \end{aligned} \quad (62)$$

As for the conditional covariance term (41), we get

$$\begin{aligned} \Gamma_2(t, T) &= \text{cov}^Q \left[\int_0^t \tilde{f}(u, u) du, \tilde{y}(t, T) \middle| \hat{\mathcal{F}}_t \right] \\ &= E^Q \left[\left(\int_0^t \tilde{f}(u, u) du - E^Q \left[\int_0^t \tilde{f}(u, u) du \middle| \hat{\mathcal{F}}_t \right] \right) (\tilde{y}(t, T) - \hat{y}(t, T))' \right]. \end{aligned}$$

Plugging in the expressions for \tilde{f} , \tilde{y} , and \hat{y} and using Fubini's theorem twice gives

$$\begin{aligned} \Gamma_2(t, T) &= E^Q \left[\int_0^t \tilde{C}(u, u) (\tilde{x}(u) - E^Q[\tilde{x}(u) | \hat{\mathcal{F}}_t]) du (\tilde{x}(t)' - \hat{x}(t)') \int_t^T \tilde{C}(t, u)' du \right] \\ &= \int_0^t \tilde{C}(u, u) E^Q[\tilde{x}(u) (\tilde{x}(t) - \hat{x}(t))'] du \int_t^T \tilde{C}(t, u)' du \\ &\quad - \int_0^t \tilde{C}(u, u) E^Q[E^Q[\tilde{x}(u) | \hat{\mathcal{F}}_t] (\tilde{x}(t) - \hat{x}(t))'] du \int_t^T \tilde{C}(t, u)' du. \end{aligned}$$

Since $\tilde{x}(t) - \hat{x}(t)$ is, by definition, orthogonal to any element which is measurable with respect to $\hat{\mathcal{F}}_t$, the term in the last line is 0. Similarly, since $\hat{x}(u)$ is orthogonal to $\tilde{x}(t) - \hat{x}(t)$, we can write

$$\Gamma_2(t, T) = \int_0^t \tilde{C}(u, u) E^Q[(\tilde{x}(u) - \hat{x}(u))(\tilde{x}(t) - \hat{x}(t))'] du \left(\int_t^T \tilde{C}'(t, u) du \right). \quad (63)$$

It is easily verified that the SDE (21) has the solution

$$\tilde{x}(t) = e^{\int_u^t \tilde{A}(\tau) d\tau} \tilde{x}(u) + \int_u^t e^{\int_s^t \tilde{A}(\tau) d\tau} \tilde{B}(s) d\tilde{w}(s), \quad (64)$$

for $t \geq u$. The process $\hat{x}(t)$ follows the analogous SDE (56) with the substitutions $\tilde{A} \rightarrow \hat{A}$, $\tilde{B} \rightarrow \hat{B}$, and $\tilde{w} \rightarrow \hat{w}$. Since \hat{w} is a Wiener process with respect to the filtration $\hat{\mathcal{F}}$ ([16]), the analogous equation to (64) holds.

Therefore,

$$\begin{aligned} & E^Q\{(\tilde{x}(u) - \hat{x}(u))(\tilde{x}(t)' - \hat{x}'(t))\} \\ &= E^Q\left\{(\tilde{x}(u) - \hat{x}(u))(\tilde{x}(u)' - \hat{x}'(u)) e^{\int_u^t \tilde{A}'(\tau) d\tau}\right\} \\ &= \bar{P}(u) e^{\int_u^t \tilde{A}'(\tau) d\tau}. \end{aligned} \quad (65)$$

Now, substitution of (65) in (63) yields

$$\Gamma_2(t, T) = \left(\int_0^t \tilde{C}(u, u) \bar{P}(u) e^{\int_u^t \tilde{A}'(\tau) d\tau} du \right) \int_t^T \tilde{C}'(t, u) du. \quad \square$$

In conclusion, putting together Lemma 5.1, relation (61), and Lemma 5.3, we have the following:

Theorem 5.4. *If $\tilde{f}(t, T)$ has dynamics as in (22) and $\hat{\mathcal{F}}_t$ is as in (51), then the projected prices $\hat{p}(t, T)$ (36) are given by*

$$\begin{aligned} \hat{p}(t, T) = & \exp\left\{-\left(\int_t^T \tilde{C}(t, u) du\right) \hat{x}(t) - \int_t^T \tilde{G}(t, u) du\right\} \\ & \cdot \exp\left\{\frac{1}{2} \left(\int_t^T \tilde{C}(t, u) du\right) \bar{P}(t) \left(\int_t^T \tilde{C}'(t, u) du\right)\right\} \\ & \cdot \exp\left\{\left(\int_0^t \tilde{C}(u, u) \bar{P}(u) e^{\int_u^t \tilde{A}'(\tau) d\tau} du\right) \int_t^T \tilde{C}'(t, u) du\right\}, \end{aligned} \quad (66)$$

where $\hat{x}(t)$ and $\bar{P}(t)$ are computed by using the Kalman filter as in Proposition 5.2 with initial conditions $\hat{x}(0) = \hat{x}_0 = 0$ and $\bar{P}(0) = 0$.

6. Filtered forward rates

In this section, we define forward rates \hat{f} , based on the filtered state \hat{x} . We show that this term structure \hat{f} is induced by the quintuple $(\tilde{f}^*, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{w})$ in the same way as \tilde{f} is induced by $(\tilde{f}^*, \tilde{A}, \tilde{B}, \tilde{C}, \tilde{w})$ and f is induced by (f^*, A, B, C, w) . Moreover, we show that the forward rates \hat{f} are indeed those associated to \hat{p} defined earlier.

In fact, in complete analogy to Propositions 2.1 and 3.1, we can define forward rates processes as

$$\hat{f}(t, T) := \tilde{C}(t, T)\hat{x}(t) + \hat{G}(t, T) \quad (67)$$

with $\hat{G}(t, T)$ given by

$$\hat{G}(t, T) := \tilde{f}^*(0, T) + \frac{1}{2} \int_0^t \hat{\beta}_T(s, T) ds \quad (68)$$

and

$$\hat{\beta}(t, T) := \left\| \int_t^T \tilde{C}(t, u) \hat{B}(u) du \right\|^2. \quad (69)$$

It is not immediately obvious that the forward rates \hat{f} thus defined are indeed those associated to \hat{p} . It turns out, though, that for our model this is indeed the case:

Theorem 6.1. *Let $\hat{p}(t, T)$ be defined by (36) and $\hat{f}(t, T)$ by (67)–(69). Then*

$$\hat{p}(t, T) = \exp \left\{ - \int_t^T \hat{f}(t, u) du \right\}. \quad (70)$$

Before we prove this theorem, we need some intermediate results.

It is well-known in system theory that the covariance $P(t) = E[x(t)x(t)']$ of the process $x(t)$ defined by (2) satisfies the Lyapunov equation

$$\frac{dP}{dt}(t) = A(t)P(t) + P(t)A'(t) + B(t)B'(t), \quad (71)$$

with the initial condition $P(0) = 0$. Analogously, the covariance \tilde{P} of $\tilde{x}(t)$ satisfies the Lyapunov equation for the pair (\tilde{A}, \tilde{B}) and the covariance \hat{P} of $\hat{x}(t)$ satisfies the Lyapunov equation for the pair (\hat{A}, \hat{B}) .

Notice next that, since $\hat{x}(t)$ and $\tilde{x}(t) - \hat{x}(t)$ are orthogonal, we have

$$\tilde{P} = E[\tilde{x}(t)\tilde{x}'(t)] = E[(\tilde{x}(t) - \hat{x}(t))(\tilde{x}(t) - \hat{x}(t))'] + E[(\hat{x}(t))\hat{x}'(t)] = \bar{P} + \hat{P}.$$

Lemma 6.2. Let $x(t)$ be the solution to (2), $C(t, T)$ be as in (4) and $P(t)$ be the covariance of $x(t)$. Then $G(t, T)$ in (5) can alternatively be written as

$$\begin{aligned} G(t, T) &= f^*(0, T) + C(t, T)P(t) \int_t^T C'(t, u) du \\ &\quad + \int_0^t C(u, u)P(u)e^{\int_u^t A'(s) ds} du C'(t, T) \\ &=: G(t, T, A, B, C). \end{aligned} \quad (72)$$

Proof. Observe first that

$$C_t(t, T) = -C(t, T)e^{\int_t^T A(s) ds} A(t) = -C(t, T)A(t).$$

Then, since the two expressions (5) and (72) of $G(t, T)$ coincide for $t = 0$, we just need to show that the partial derivatives in t are equal. Thus, from (72),

$$\begin{aligned} G_t(t, T) &= -C(t, T)A(t)P(t) \int_t^T C'(t, u) du + C(t, T) \frac{dP}{dt}(t) \int_t^T C'(t, u) du \\ &\quad - C(t, T)P(t)A'(t) \int_t^T C'(t, u) du \\ &\quad - C(t, T)P(t)C'(t, t) + C(t, t)P(t)C'(t, T) \\ &\quad + \int_0^t C(u, u)P(u)e^{\int_u^t A'(s) ds} A'(t) du C'(t, T) \\ &\quad - \int_0^t C(u, u)P(u)e^{\int_u^t A'(s) ds} du A'(t) C'(t, T) \\ &= C(t, T) \left[-A(t)P(t) + \frac{dP}{dt}(t) - P(t)A'(t) \right] \int_t^T C'(t, u) du \\ &= C(t, T)B(t)B'(t) \int_t^T C'(t, u) du, \end{aligned}$$

which is (10), as wanted. \square

In a completely similar manner, we have that

$$\tilde{G}(t, T) = G(t, T, \tilde{A}, \tilde{B}, \tilde{C}) \quad (73)$$

and

$$\hat{G}(t, T) = G(t, T, \tilde{A}, \hat{B}, \tilde{C}).$$

Proof of Theorem 6.1. Since (70) obviously holds for $t = T$, it suffices to show

$$-\frac{\partial}{\partial T} \log \hat{p}(t, T) - \tilde{C}(t, T)\hat{x}(t) = \hat{G}(t, T). \quad (74)$$

Using (66), we can write

$$-\frac{\partial}{\partial T} \log \hat{p}(t, T) - \tilde{C}(t, T) \hat{x}(t) = \tilde{G}(t, T) - \tilde{C}(t, T) \bar{P}(t) \int_t^T \tilde{C}'(t, u) du \\ - \left\{ \int_0^t \tilde{C}(u, u) \bar{P}(u) e^{\int_u^t \tilde{A}'(s) ds} du \right\} \tilde{C}'(t, T).$$

Plugging in (73) yields

$$-\frac{\partial}{\partial T} \log \hat{p}(t, T) - \tilde{C}(t, T) \hat{x}(t) = \tilde{f}^*(0, T) \\ + \tilde{C}(t, T) \tilde{P}(t) \int_t^T \tilde{C}'(t, u) du + \left\{ \int_0^t \tilde{C}(u, u) \tilde{P}(u) e^{\int_u^t \tilde{A}'(s) ds} du \right\} \tilde{C}'(t, T) \\ - \tilde{C}(t, T) \bar{P}(t) \int_t^T \tilde{C}'(t, u) du - \left\{ \int_0^t \tilde{C}(u, u) \bar{P}(u) e^{\int_u^t \tilde{A}'(s) ds} du \right\} \tilde{C}'(t, T)$$

and using the fact that $\tilde{P}(t) - \bar{P}(t) = \hat{P}(t)$,

$$-\frac{\partial}{\partial T} \log \hat{p}(t, T) - \tilde{C}(t, T) \hat{x}(t) = \tilde{f}^*(0, T) \\ + \tilde{C}(t, T) \hat{P}(t) \int_t^T \tilde{C}'(t, u) du + \left\{ \int_0^t \tilde{C}(u, u) \hat{P}(u) e^{\int_u^t \tilde{A}'(s) ds} du \right\} \tilde{C}'(t, T) \\ = G(t, T, \tilde{A}, \hat{B}, \tilde{C}) = \hat{G}(t, T),$$

which completes the proof. \square

7. Conclusion

We have shown that it is possible to define a filtered term structure in a general, model-free way, when a candidate for a numeraire is not observed (Section 4).

Although not themselves linear-Gaussian, the filtered prices can be computed by application of the standard Kalman-filter in the specific linear-Gaussian setting (Section 5).

There is a complete analogy among the term structures f , \tilde{f} and \hat{f} . The filtered prices could, instead of the “economic” definition of Section 4, alternatively be defined by mathematical analogy according to (67). It turns out—but is not obvious—that, in our setup, both definitions are equivalent (Section 6).

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